Evidence for the fourth P_{11} resonance predicted by the constituent quark model

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It is pointed out that the third of five low-lying P_{11} states predicted by a constituent quark model can be identified with the third of four states in a solution from a three-channel analysis by the Zagreb group. This is one of the so-called "missing" resonances, predicted at 1880 MeV. The fit of the Zagreb group to the $\pi N \rightarrow \eta N$ data is the crucial element in finding this fourth resonance in the P_{11} partial wave.

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The study of nucleon resonances (N^*) involves two steps. First, the positions and the decay widths of the N^*'s must be extracted from the available experimental data of πN and γN reactions. This step is usually accomplished by performing a partial wave analysis (PWA). The parallel step is to develop a theoretical explanation of the extracted resonance parameters. This is most commonly pursued by developing various quark models.

The PWA of πN scattering has a long history. A number of approaches have been developed with various levels of sophistication in implementing some theoretical constraints in order to offset the difficulties due to the lack of complete and accurate data. The most elaborate early PWA analyses were performed mainly for πN elastic scattering using either single-channel dispersion relations [1] or a multi-channel, multi-resonance, unitary model [2]. Recent PWA's [3,4,5,6] are based on some variations of these approaches, but using updated data sets. These efforts have led to some revisions of the resonance parameters listed by Particle Data Group (PDG) [7], and have triggered debates on some resonance parameters. In particular, the S_{11} and P_{11} resonances have been frequently discussed, and this has stimulated new experimental efforts in order to resolve the existing controversies. In this paper, we focus on the πN partial wave P_{11}, and discuss how the quark-model predictions of Refs. [8,9,10,11], which contain more states than listed by the PDG, are consistent with a PWA analysis [5,12,13] based on a multi-channel, multi-resonance, unitary model first developed by Cutkosky and collaborators [2].

In Refs. [12,13], it was pointed out that two PWA solutions can be found within a three-channel ($\pi N, \eta N, \pi^2 N$) unitary model. They differ mainly in the number of P_{11} resonances and their corresponding branching ratios. The analysis has been repeated in Ref. [5] using an improved S_{11} amplitude [14], which is crucial in constraining the fit to the $\pi N \to \eta N$ cross sections near threshold. We are again able to find two solutions, as shown in Table 1. The resonance parameters are essentially the same for the three-resonance and four-resonance solutions, with the exception of the P_{11} channel. In particular, the branching ratios to the ηN and $\pi^2 N$ channels for the second P_{11}(1710 MeV) state satisfy $x_{\eta N} \gg x_{\pi^2 N}$ for the three-resonance solution, but $x_{\pi^2 N} \gg x_{\eta N}$ for the four-resonance solution.

To further distinguish these two solutions, it is necessary to extend the present analysis by replacing the $\pi^2 N$ channel with an explicit treatment of the inelastic data in each of the channels $\pi\Delta$, ρN , $\sigma[(\pi\pi)_{l=0}]N$, etc. This highly non-trivial task, while beyond the scope of this investigation, was carried out in the analysis of Manley and Saleski [4]. The resulting total $\pi^2 N$ branching ratio is, therefore, more strongly constrained by the data than that of the Zagreb analysis. We therefore assume that the more acceptable solution of the Zagreb

analysis is that which yields a $\pi^2 N$ branching ratio closer to that of Manley and Saleski. This is the four-resonance solution listed in Table 1. We note here that the data of $\pi N \to \eta N$ are not included in Manley and Saleski's analysis, but are treated with great care in the Zagreb analysis. When this data and the $x_{\pi^2 N}$ values from Manley and Saleski are put together, the four-resonance solution is strongly favored. This example clearly demonstrates that some "missing" resonances are sensitive to particular channels, and can be discovered only when the data associated with those channels are included in the analysis.

The results of constituent quark models are useful for interpreting the results shown in Table 1. In particular, models which treat the three light quarks as symmetric predict the existence of several positive-parity excited baryon states in the 1700-2000 MeV region which have not previously been identified in PWA's. In particular, in the P_{11} partial wave in πN, a model which perturbs around the spectrum of two three-dimensional harmonic oscillators with hyperfine and linear confinement corrections [15] found four P_{11} excited states, which are part of the $N = 2$ band of positive-parity excited states. Prior to configuration mixing by the perturbations, two are radial excitations of the nucleon, with either totally-symmetric or mixed-symmetry spatial wavefunctions, one is a total orbital angular momentum $L = 2$ state with quark-spin-$\frac{3}{2}$, and the fourth is an $L = 1$ state with quark-spin-$\frac{1}{2}$. After mixing, the two radial excitations are identified with the two low-lying PDG states $P_{11}(1440)$ and $P_{11}(1710)$ on the basis of their perturbed masses. Also, an analysis of the πN decay amplitudes of these states using a decay model where point-like pions are emitted directly from the quarks [16] showed that these two states should have stronger amplitudes to couple to the πN channel than the the remaining two 'missing' states in the $N = 2$ oscillator band. The more massive of the latter has the smallest predicted πN amplitude.

These predictions for masses and πN decay branches are essentially confirmed and extended in the work of Refs. [8,9] and [10,11]. These models went beyond perturbing around the $N = 2$ oscillator band in the description of the spectrum, and used a microscopic quark model of strong decays (the $^3P_0$ model) which ascribes structure to the emitted meson. We will focus here, for definiteness, on the model of Refs. [10,11], which predicts four P_{11} states below 2000 MeV (at 1540, 1770, 1880, and 1975 MeV), and many additional excited states with wavefunctions predominantly in the $N = 4$ band, the lightest of which is at 2065 MeV.

From Table 1 it can be seen that the first three model states at 1540, 1770 and 1880 MeV correspond nicely to those of the four-resonance solution of Zagreb analysis, while the third model state at 1880 MeV can not be identified with any of the PDG resonance parameters in the first column. The PDG parameters are based mainly on analyses which

do not "explicitly" account for the $\pi N \to \eta N$ reaction data. From Table 1 we see that the third model state at 1880 MeV has a substantial predicted partial decay width to ηN channel, and hence should be more easily identified in the Zagreb analysis. It is possible that this "missing" resonance could also be found by the multi-channel analysis of Manley and Saleski if the data of $\pi N \to \eta N$ are included.

The fourth model state at 1975 MeV does not correspond to any PDG state, and is not found in the Zagreb solutions. This is not surprising, since this state is predicted to have very weak decay widths for the πN and ηN channels. It is possible that this state is more sensitive to a particular channel of the $\pi^2 N$ continuum, like $\pi\Delta$ [11], and can only be identified in an analysis in which the data for that particular inelastic channel are included explicitly. However, the quality of the $\pi^2 N$ data at $W \simeq 2000$ MeV is not good enough for an accurate determination of the partial cross section to each individual inelastic channel. This is perhaps the reason why this state is also not found in the multi-channel analysis of Manley and Saleski (included in the PDG results).

A substantial discrepancy is found for the branching ratios x_η and x_{π^2} of the highest mass resonance at ~ 2100 MeV. However, the branching ratios extracted from the PWA at such high energies are heavily dependent on the input data of $\pi N \to \pi\pi N$ and $\pi N \to \eta N$ reactions in the PWA analyses, and the quark model branching ratios should be considered upper bounds as some channels have been omitted from Ref. [11]. It is also likely that there are substantial corrections to the constituent quark model from baryon-meson loops, and possible excitations of the glue at higher masses in the P_{11} partial wave [17], which are ignored here. Therefore, one expects improved agreement between the models when the input becomes more constrained, and more is known about the structure of higher-mass states.

The results of analyses such as the one being discussed here are also very important for helping to distinguish between different models of the nucleon and its excitations. For instance, the so-called diquark models predict fewer states in the excitation spectrum [18], because there are fewer degrees of freedom in the models. However, such models still predict more states than observed experimentally. In particular, they also predict a missing P_{11} state near the one identified here. To the best of our knowledge, the only model that lacks such a state is that of Ref. [19].

In conclusion, we identify the need for a fourth resonance in the P_{11} partial wave when using the current πN and ηN data base for a multi-channel, multi-resonance PWA [5]. The extracted positions and branching ratios are in reasonable agreement with quark-model

predictions [11], given the insufficiently determined input.

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TABLE I. Resonance parameters of the phenomenological [5] and the quark [10,11] models. The first column gives the masses, widths, and pion-decay branching fractions from the latest PDG compilation [7].

						Zagreb group Ref. [5]					**quark model of Refs. [10,11]**				
States	Three P_{11} resonances					Four P_{11} resonances					Five P_{11} resonances				
$L_{2I,2J}$ $(^{x_\pi}_{\mathrm{Mass/Width}})$	Mass (MeV)	Width (MeV)	x_π (%)	x_η (%)	x_{π^2} (%)	Mass (MeV)	Width (MeV)	x_π (%)	x_η (%)	x_{π^2} (%)	Mass (MeV)	Width (MeV)	x_π (%)	x_η (%)	x_{π^2} (%)
$S_{11}(^{38}_{1535/120})$	1552(16)	181(12)	45(7)	51(6)	4(4)	1553(8)	182(25)	46(7)	50(7)	4(2)	1460	645	34	66	0
$S_{11}(^{61}_{1650/180})$	1653(12)	205(18)	76(6)	19(7)	5(3)	1652(9)	202(16)	79(6)	13(5)	8(3)	1535	315	47	39	14
$S_{11}(^{9}_{2090/95})$	1809(21)	380(50)	30(7)	20(6)	50(8)	1812(25)	405(40)	32(6)	22(10)	46(9)	1945	595	6	2	89
$P_{11}(^{51}_{1440/135})$	1437(21)	401(40)	60(7)	0(0)	40(6)	1439(19)	437(14)	62(4)	0(0)	38(4)	1540	425	97	0	3
$P_{11}(^{12}_{1710/120})$	1713(25)	160(20)	20(5)	**78(3)**	2(8)	1729(16)	180(17)	22(24)	6(8)	**72(23)**	1770	305	6	22	**72**
P_{11}	-	-	-	-	-	1740(11)	140(25)	28(34)	12(9)	**60(35)**	1880	155	5	18	**76**
P_{11}	-	-	-	-	-	-	-	-	-	-	1975	45	8	0	92
$P_{11}(^{9}_{2100/200})$	2161(30)	380(60)	14(6)	**82(8)**	4(6)	2157(42)	355(88)	16(5)	**83(5)**	1(1)	2065	270	22	1	**77**
$D_{13}(^{54}_{1520/114})$	1522(8)	130(10)	50(4)	0.1(0.1)	49(4)	1522(8)	132(11)	55(5)	0.1(0.1)	45(5)	1495	115	64	0	36
$D_{13}(^{8}_{1700/110})$	1809(15)	138(30)	10(3)	10(3)	80(6)	1817(22)	134(37)	9(6)	14(5)	77(9)	1625	815	4	0	96
$D_{13}(^{6}_{2080/265})$	2001(16)	610(50)	15(8)	6(2)	79(7)	2048(65)	529(13)	17(7)	8(3)	75(7)	1960	535	12	6	81

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